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Are the Mediterranean forests in Southern Europe threatened from ozone?

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Abstract

The influence of air pollutants on ecosystems in Europe has been studied for over two decades in the Western and Nordic countries and in the Alps. The impacts of air pollutants on Mediterranean forest ecosystems (evergreen sclerophyllous forests and maquis) are poorly understood. The Mediterranean climate encourages the generation of high concentrations of ozone – now recognised to be the most prevalent and damaging air pollutant to which vegetation is exposed in many regions. In this paper, we examine the way in which many of the typical morphological and ecophysiological features of Mediterranean vegetation influence ozone impacts, plus the way in which the combination of environmental stresses to which Mediterranean vegetation is exposed in the field affect responses to ozone. Sclerophyllous Mediterranean species (typified by leaves with dense mesophyll, little intercellular air space and containing an abundance of primary, e.g. ascorbate, and secondary metabolites, e.g. tannins and phenylpropanoids, that are capable of protecting key biomolecules from oxidative stress) might be expected to be hardier than their counterparts more typical of the relatively mesic environments of Northern and Continental Europe. Moreover, soil water shortage during the height of summer causes partial stomatal closure for lengthy periods each day. As a result, vegetation may avoid taking-up the ozone when concentrations are at their highest. There are several confirmed reports of visible symptoms of ozone damage (chlorotic mottle, necrosis, reddening etc.) on important crops and forest trees. The significance of these observations is discussed, along with the way in which ongoing changes in the Mediterranean environment may affect the future impacts of rising ozone concentrations on vegetation.

Introduction

Mediterranean ecosystems are considered intrinsically fragile (Naveh, 1995) because of the climate (discontinuous rain, with prolonged periods of soil and atmospheric drought in summer; high summer temperatures; intense solar radiation) and edaphic conditions (often thin soils of poor nutritional quality – particularly scarce in nitrogen and phosphorus) to which they are exposed in their natural environment. In addition, they have been subjected to such extensive anthropogenic pressures that their original features are often scarcely recognizable. As far as the impact of gaseous pollutants are concerned, one particularly damaging form of air pollution – the photochemical generation of oxidants (and in particular, ozone) - finds the most favourable environment for its development and its diffusion in Mediterranean climates (Butkovic *et al*., 1990). The detrimental effects of this type of air pollution on natural and managed ecosystems are well documented in Europe (Skärbi *et al*, 1998) and North America (Chappelka & Samuelson, 1998). In the Mediterranean basin there have been several studies which sought to quantify effects on the yield of agricultural crops (Benton *et al*., 2000), but the impacts of photochemical oxidant pollution on forests and other natural or semi-natural ecosystems in the Mediterranean remain largely unresearched (Bussotti & Ferretti, 1998).

In this context, we review herein what is known about the impacts of ozone on Mediterranean plants and ecosystems and assess the potential risks posed by photochemical oxidants as well as the way in which specific features of Mediterranean plants, and the environment to which they have adapted, might be expected to influence the impacts of ozone.

Ozone climatology in the Mediterranean region

In the Mediterranean basin, the persistence during summer months of the Azores anti-cyclone over Europe, and the resulting atmospheric stability, with high temperatures, low relative humidity and high levels of solar irradiation, favour a massive photochemical production of ozone in the lower troposphere, with hourly concentration peaks that frequently reach 150-220 ppb or more (Chaloulakou *et al*., 1999).

In rural and suburban areas located downwind from precursor emission sources, ozone reaches higher concentrations than those recorded in urban areas. In urban zones the presence of considerable NO emissions favours a titration reaction, reducing concentration of O_3 produced. In rural areas, where there are no significant pollutant sources, NO emissions occur far less frequently and the advection of NO_2 from the emission areas feeds the photolysis cycle and ozone production increases as a consequence. Breezes activated by the sea-coast or mountain-valley thermobaric differences contribute then to a redistribution of ozone throughout the region, affecting even remote areas such as coastal and mountain rural zones. The transport of ozone and its precursors from the highly anthropized zones to remote forest sites by summer breezes has been highlighted by several different studies carried out in mountain areas south of the Alps and in the Italian plains along the Po river (Bacci *et al*., 1990; Gerosa *et al*., 1999), in the Mediterranean coastland and inland regions of Spain (Martín *et al*., 1991), Italy (Lorenzini *et al*., 1995), Greece (Güsten *et al*., 1988), and in the South-Eastern Mediterranean (Alper-Siman *et al*., 1997).

During the day, sea breezes can transport inland ozone formed in the urban and industrial coastal areas for up to 100 km and further (Millán *et al*., 1991, 1996; Lalas *et al*., 1983). The evening sea breezes push the masses of air offshore where the deposition rate is so slow that ozone accumulates and is transported back to the coast the following day, when the daytime sea breezes resume, thus setting in motion mechanisms of photo-oxidant recirculation (Fortezza *et al*., 1993; Alper-Siman *et al*., 1997). A similar mechanism occurs where orographic barriers are present and during the day, the ozone plume is pushed upwards by ascending breezes. The formation of nocturnal inversion layers hinders its deposition and this gives rise to accumulated masses of ozone-rich air at altitudes ranging from 500 m to 2000 m above ground (Schlager *et al*., 1992). When phenomena of subsidence occur or when catabatic, or descending, currents drag these masses vertically downwards, they may actually contact the ground and give rise to peak ozone exposures, usually in the evening. Multiple layers of ozone accumulation have also been observed above the inland in coastal areas (Georgiadias *et al*., 1994; Millán *et al*., 1996; Sanz & Millán, 1998). Ozone concentration is highest in spring and summer, and lowest in winter. Sudden increases of ozone concentration, however, can be observed in winter as well, when phenomena causing a vertical mixing of the atmosphere occur, due to strong descending winds (such as föhn/stau in mountain areas) or to intrusions of air from the lower stratosphere / free troposphere, which are not infrequent in spring (Davies & Schuepbach, 1994).

Mediterranean vegetation is a strong emission source of isoprenoid compounds (monoterpenes and isoprene) released into the atmosphere (Street *et al*., 1997; Peñuelas & Lusià, 1999). These compounds play an important role in the plants' defense mechanisms against heat stress (Loreto *et al*., 1998). Yet, these natural emissions are a considerable source of active carbon and can therefore play a crucial role in the formation and persistence of atmospheric pollutants and greenhouse gases such as carbon monoxide and the same ozone (Fehsenfeld *et al*., 1992). The interaction of ozone with the crowns' emissions gives rise to other potentially toxic compounds such as carbonyl compounds and radicals (Fruekilde *et al*., 1998).

Critical load for forests, AOT40 of 10,000 ppb.h (accumulated hourly exposures of O_3 over a threshold of 40 ppb in daylight hours from April to September; Kärenlampi & Skärby, 1996) is vastly exceeded during the growing season in the Mediterranean and sub-alpine region, as is shown in the simulated experiments done using the EMEP model (Hjellbrekke, 2000) and by regional estimates prepared in individual countries (Posch *et al*., 1998). Furthermore, in many sites across southern Europe the hourly concentration of O_3 in summer never drops below the threshold of 40 ppb (Velissariou & Skretis, 1999). Table 1 shows some relevant data in Mediterranean sites.

Ecological behaviour of Mediterranean woody plants in relation to ozone

The phytotoxic action of ozone depends on the way it is absorbed by the leaves and, therefore, how it spreads in the mesophyll. Mediterranean vegetation consists to a large extent of coriaceous leaf plants (evergreen sclerophyllous vegetation). The foliar structure of Mediterranean evergreens is usually characterized by the presence of 2-3 layers of palisade mesophyll and a thinner layer of spongy tissue (see De Lillis, 1991). This is a strategy which limits the transpiration, but in doing so it also limits the absorption of CO_2 and, therefore, of atmospheric pollutants. The typical Mediterranean conditions enhance the sclerophylly. In fact, plants growing in dry, sterile environments, and/or subjected to high radiation intensity usually have greater foliar thickness and density (Gutschick, 1999), thus suggesting an infra-specific sensitivity: ozone exerts a lesser impact on trees growing under conditions of stress (see also Davison & Barnes, 1998). In addition, at their southernmost distribution area, several species largely distributed in Europe (European beech: Bauer *et al.*, 1997; silver fir: Rinallo & Gellini, 1989) differ from the central European provenances in that their leaves are more sclerophyllous. In the case of silver fir (Larsen, 1990) and European beech (Paludan-Müller *et al.*, 1999) a reduced sensitivity to ozone and other air pollutants has also been observed in the southern provenances .

Stomatal activity is considered the key element determining the sensitivity of a particular species to ozone (Emberson *et al.*, 2000). Usually the prevailing weather conditions induce a marked reduction in stomatal conductance in Mediterranean vegetation during the height of summer. The highest levels of ozone experienced in the field usually coincide with the time that non-managed plants in the Mediterranean suffer the greatest degree of water deficit, and their stomata are close. However, the behaviour of individual species varies considerably (Rhizopoulou & Mitrakos, 1990; Tretiach, 1993; Gucci *et al.*, 1999) in their capacity to tolerate drought before resorting to stomatal closure. As a consequence, those species that exhibit the greatest ability to maintain, or reactivate, gas exchange under conditions of water stress, might be expected to be the most affected by ozone. Generally speaking, the deciduous trees narrow their stomata to higher water potential than the evergreen ones. For example, in *Quercus ilex* leaves stomata remain open much longer than in deciduous oaks (Salleo & Lo Gullo, 1990; Acherar *et al.*, 1991). Between the evergreen shrubs, *Phillyrea latifolia* L. shows the highest tolerance to water stress.

The way in which the combination of ozone and soil water deficit affect stomatal conductance are, however, much more complex than might first be perceived since recent evidence suggests that exposure to the pollutant can impair stomatal performance under conditions of soil water deficit (Maier-Maercker, 1998) and the outcomes in terms of cost/benefit analysis probably depend, at least to some extent, on the timing of the stress to which the plant is exposed, genotype and the intensity of the stress to which the plant is exposed (Maier-Maerker, 1998).

Biochemical processes leading to compensation (for the damaged tissues) and to protection (by means of the production of anti-oxidant substances) presuppose considerable metabolic costs (Heath, 1999), which therefore lead to an increase in carbohydrate

Table 1. Number of hours and days exceeding 200 µg m^{-3}, maximum concentrations and AOT40 (April-September, daylight) in 1998 at selected EMEP monitoring sites (from Hjelbrekke, 2000 modified)

Site	Country	Latitude	Longitude	Elevation	>200 µg m^{-3}		Conc. max		AOT40
				m asl	hours	days	µg m^{-3}	Month	ppb.h
San Pablo	Spain	39 32 55 N	04 21 07 W	917	0	0	151	August	21469
Tortosa	Spain	40 49 14 N	00 29 29 E	50	0	0	137	May	7968
Logroño	Spain	42 27 28 N	02 30 11 W	445	0	0	176	June	20694
Viznar	Spain	37 14 17 N	03 32 00 W	1265	0	0	189	July	39934
Montelibretti	Italy	42 06 00 N	12 38 00 E	48	25	21	291	May	24945
Ispra	Italy	45 48 00 N	08 38 00 E	209	33	12	309	July	24630
Iskrba	Slovenia	45 34 00 N	14 52 00 E	520	0	0	183	August	21342
Zavodnje	Slovenia	46 25 43 N	15 00 12 E	770	0	0	164	May	17427
Kovk	Slovenia	46 07 43 N	15 06 50 E	600	0	0	168	July	6805

consumption, with carbohydrates being used for purposes other than plant growth. From this point of view, primary (ascorbate) and secondary metabolites (including tannins and other phenolic substances) play an important role (Polle & Rennenberg, 1992). Secondary metabolites are normally present in many plants growing in a Mediterranean climate (Karabourniotis *et al*., 1993), and their concentrations increase under environmental stress (Gravano *et al*., 2000b; Tattini *et al*., 2000). Since the same substances are involved in detoxification from ozone stress processes (Kangasjärvi *et al*., 1994), plants already endowed with these substances would appear to have a greater protection against this pollutant.

Sensitivity and visible symptoms

In forest tree leaves visible symptoms attributable to chronic exposure to ozone were described for the first time in the mountain pines of a Mediterranean-type climate region, the Southwest of the United States (Miller *et al*., 1963, Miller & McBride, 1999). These symptoms consisted in localized yellowing (chlorotic mottles) which degenerated into necrotic patches, and only in the most severe cases did needle tip necrosis ensue. These yellowings were usually associated with a degeneration of the mesophyll (Evans & Miller, 1972). Among the woody species of Southern European flora and the Mediterranean basin, basal plane pines are the most sensitive to the action of photo-oxidants. Already in the early 1980s Naveh *et al*. (1980) described symptoms in *Pinus pinea* L. and *Pinus halepensis* Mill. in Israel. The most evident and widespread symptoms were later described in *Pinus halepensis* in Spain (Gimeno *et al*., 1992; Barnes *et al*., 1999), in Greece (Velissariou *et al*., 1992; Gimeno *et al*., 1992) and in Italy (Soda *et al*., 2000). *Pinus halepensis* needles develop a very typical symptomatology (chlorotic mottles), similar to that described by the above-mentioned American researchers. Sanz *et al*. (2000) found that the distribution pattern of ozone visual injuries (chlorotic mottle) in *Pinus halepensis* correlated with the penetration of the pollutant transported by the sea-breeze into coastal valleys in Eastern Spain.

Broadleaved trees develop a varied symptomatology which has been described in several pictorial atlases and handbooks (see Skelly *et al*., 1987; Flagler, 1998; Innes *et al*., 2001). In Europe the most widespread and evident symptoms were reported in Southern Switzerland (Skelly *et al*., 1998) and in adjacent areas in Northern Italy (Cozzi *et al*., 2000; Gravano *et al*., 2000a). These symptoms were validated by means of open top chamber experiments (VandeRHeyden *et al*., 2001). In the Mediterranean region the majority of available reports come from Spain (Skelly *et al*., 1999; Sanz & Millán, 2000) where several evergreen shrubs were found to be sensitive. Table 2 gives an overall picture of the woody species in which symptoms were observed and the countries where the observations took place.

The sensitivity to ozone of Mediterranean species has also been investigated, by means of tests performed in controlled and/or semi-controlled environments, in terms of physiology and/or ultrastructure (Table 3). One can observe that the most widely studied species is *Pinus halepensis*, but it is difficult to extrapolate these findings to the field because almost all experiments were conducted with seedlings, whose response to ozone differs from that of adult trees (Kolb *et al*., 1998). In some cases, researchers have even used seedlings less than a year old, so that their foliar morphology is different from older trees. Further, the concentrations and exposure periods applied in these experiments are often highly unrealistic (concentrations greater than 100 ppb, although not rare, are normally only observed as hourly peak rates). Lastly, these experiments are performed in optimal soil moisture conditions, whereas Mediterranean species in summer are normally subjected to drought. Experiments only recently have been performed on typical evergreen broadleaved trees (Table 3). Among these, *Arbutus unedo* L. is potentially the most sensitive species.

The results of the investigations listed in Table 3 are largely specie-specific and are influenced by the experimental conditions. The most common results are the reduction of stomatal conductance and photosynthesis, as well as the content in chlorophyll. Detoxifying compounds (peroxidase, ascorbate) increase. The ozone effects in combination with water stress are controversial in experimental conditions.

Discussion and Conclusions

At first glance it would appear that Mediterranean forests are well endowed with a good resilience to ozone. The ecophysiological behaviour of trees and their foliar structure (well-balanced with the climatic and edaphic conditions of the environment), as well as the abundance of detoxifying metabolites in many species, allows them to limit the stomatal absorption of ozone and to repair any injury to their leaves very quickly. Evergreen Mediterranean plants are able to maintain a stomatal activity under moderate water stress, but display their strongest photosynthetic activity during the equinoctial seasons (Tretiach, 1993), particularly when

Table 2. Some of the most important native (or naturalized) tree and shrub species that showed ozone-like symptoms in Mediterranean countries.

Species	Spain *ref*	Italy *ref*	Greece *ref*	Ticino *ref*	Israel *ref*
Abies cephalonica			7; 11		
Acer platanoides				9	
Acer pseudoplatanus		1		9	
Ailanthus altissima	9	5; 2		9	
Arbutus unedo	9				
Alnus incana				9	
Betula pendula				9	
Carpinus betulus		1		9	
Cornus spp.	9	1		9	
Corylus avellana	9	1		9	
Crataegus spp.				9	
Fagus sylvatica		2		9	
Frangula alnus				9	
Fraxinus excelsior		6; 2		9	
Fraxinus ornus	9	1			
Juglans regia	9				
Morus spp.				9	
Myrtus communis	9				
Pinus halepensis	4	10	4; 12		8
Pinus pinea					8
Pistacia lentiscus	9				
Pistacia terebintus	9				
Populus spp.	9	3		9	
Prunus amygdalus	*9*				
Prunus avium		6; 2		9	
Prunus serotina				9	
Prunus spinosa	9	1			
Robinia pseudoacacia		2			
Rhamnus spp.				9	
Rosa spp.	9	1		9	
Salix spp.		1		9	
Sambucus spp.	9			9	
Tilia spp.		1		9	
Ulmus glabra		2		9	
Viburnum spp.	9	1		9	

Reference

1. Bussotti (pers.comm.)
2. Cozzi et al., 2000
3. Fumagalli et al., 1989
4. Gimeno et al., 1992
5. Gravano et al., 1999;
6. Gravano et al., 2000a
7. Heliotis et al., 1988
8. Naveh et al., 1980
9. Skelly et al., 1999
10. Soda et al., 2000
11. Velissariou and Skretis, 1999
12. Velissariou et al., 1992

Table 3. Sensitivity to air pollution of mediterranean forest species, and relevant experimental conditions in chronological order (modified and updated from Bussotti and Ferretti, 1998)

Species	Reference	Kind of experiment	Treatment	Results
Citrus limon	Grimaldi e Polizzi, 1989	Plants in fumigation chambers	Ozone: 0.6 – 0.7 ppm per 24 h.	Necrotic patches and ultrastructural alterations of mesophyll.
Pinus halepensis	Gimeno *et al.*, 1992	Field observations and controlled environment chambers (5 years-old seedlins)	Ozone both in field (up to 210 ppb) and in controlled conditions (70 ppb average for 7 h at day within 2 months)	Visible symptoms (chlorotic mottles)
Pinus halepensis	Wellburn and Wellburn, 1994	2-year-old seedlings in fumigation chambers	Episodic (up to 5 d) ozone exposure (up to 120 ppb) during a growing season	Visible symptoms (chlorotic mottles); starch accumulation in the endodermis; crushing of the phloem sieve cells.
Pinus halepensis	Anttonen *et al.*, 1994	18 month-old seedlings in controlled-environmental chambers	Ozone (150-600 ppb) over a period of 2-16 days	Low ozone exposure: increase in myristic and palmitic acid; reduction in chloroplast size and darkening of stroma;High ozone exposure: reduction of linolenic acid; disruption of chloroplast membranes.
Pinus halepensis	Manes and Blasi, 1995	4 year-old seedlings in fumigation chambers	Ozone: 150 ppb per 10 weeks, per 6 days week^{-1}, per 7 h d^{-1}	Reduction of photosynthetic activity.
Pinus halepensis	Elvira *et al.*, 1995	1-3 year-old seedlings in open top chambers	Ozone (filtered air; not filtered; ambient air + 40 ppb ozone). Summer treatments (7 h at day, 5 d at week) over a three year period	Visible symptoms in the second year of exposure. Reduction in net photosynthesis, stomatal conductance, chlorophyll, N and P.
Pinus halepensis	Peñuelas *et al.*, 1995	1-3 year-old seedlings in open top chambers	Ozone (filtered air; not filtered; ambient air + 40 ppb ozone). Summer treatments (7 h at day, 5 d at week) over a three year period	Decrease of chlorophyll content in the needles during the summer.
Pinus halepensis	Scalet *et al.*, 1995	3 year-old seedlings in growth chambers	Ozone (100 ppb) and simulated acid rain (pH 3.4) over a 2 months period	Increase of peroxidase activity, polyamine, putrescine and spermidine in 1-year needles both in combined and ozone treatments

Pinus halepensis	Gerant *et al.*, 1996	3 year-old seedlings in growth chambers	Ozone (100 ppb) 14 h d^{-1} during 3 months	Decrease in specific activity of whole plant. Increase of mitochondrial activity. With drought stress Rubisco activity decreases.
Pinus halepensis	Diaz *et al.*, 1996	2 year-old seedlings in fumigation chambers	Ozone (50 ppb) and SO_2 (40 ppb) single and together over 1 year.	No significant effects of single treatments on root and total biomass. In combination O_3 and SO_2 reduce of 25% the total biomass and affect the mycorrhizae.
Pinus halepensis	Wellburn *et al.*, 1996	3-year-old seedlings in solardomes	Episodic ozone (100-110 ppb) fumigations	Depression of nitrate reductase; accumulation of polyamines, glutathione and ascorbate in current year needles. Drought and air pollution reduce total phenols and glutathione.
Pinus halepensis	Anttonen *et al.*, 1998	18 month-old seedlings in open air experiment.3 years-old seedlings in environmental growth chamber.	Ozone (1.2-1.8 x ambient concentration) over 1-2 growth seasons.Ozone (150 ppb) for 5 weeks (12 h d)	Increase in diffusive stomatal conductance. No significant decrease in starch content.Visible symptoms. Decrease in starch content. Increase in diffusive stomatal conductance.
Pinus halepensis	Inclán *et al.*, 1998	2 years-old seedlings in open top chambers	Ozone (filtered air; ambient air + 40 ppb ozone). Summer treatments (7 h at day, 5 d at week) over a 20 months period.Drought treatments.	Antagonistic effects on gas exchange rates between ozone and drought treatments.
Pinus halepensis	Elvira et al., 1998	1 year-old seedlings in OTC	Ozone: charcoal-filtered air (CFA); non-filtered air (NFA); non-filtered air + 40 ozone 40 ppb(NFA+40). Three consecutive summers (9 h at day, 5 d at week).	Increase in extracellular and total peroxidase activities and in zeaxanthin levels in NFA+40 treatment.
Quercus ilex	Manes *et al.*, 1998	4 year-old seedlings in growth chambers	Ozone (0, 65, 175, 300 ppb) per 4 days, 6 h d^{-1}	Photosynthesis, chlorophyll fluorescence, POD activities are not influenced in treatments lower than 300 ppb
Pinus halepensis	Kytoviita et al., 1999	9 week-old seedlings (in symbiosis with *Paxillus involutus*) in growth chambers	Ozone 200 ppb + CO_2 700 µm for 68 days	Ozone diminishes the growth both of seedling and fungus. CO_2 does not ameliorate the negative effects of ozone.

Pinus halepensis	Fontaine et al., 1999	3 year-old seedlings in phytotrone	Ozone 200 ppb over three months	No effects on CO_2 assimilation or stomatal conductance. Reduction of Rubisco activity.
Pinus halepensis	Manninen et al., 1999	2 year-old seedlings in OTC	Charcoal filtered air (CFA); non filtered air (NFA); non filtered air + ozone 50 ppb (NFA+O_3); ambient air (AA), 24 h d^{-1} during a growth season.	Chlorotic mottling, reduction of chlorophyll and carotenoid concentration in C and C+1 needles.
Quercus ilex ssp ilex; *Q. ilex* ssp. *ballota*; *Olea europaea* ssp. *sylvestris*; *Ceratonia siliqua*; *Arbutus unedo*	Inclán *et al*., 1999	2 year-old seedlings in OTC	Charcoal filtered air (CFA); non filtered air (NFA); non filtered air + ozone 40 ppb (NFA+40), 9 h d^{-1} (10:00-18:00) during 1 year.	Visible symptoms on *Q. ilex* ssp. *ballota* and *A. unedo* (NFA+40). Reduction of plant biomass on *Q. ilex* ssp. *ballota* and *O. europaea* ssp. *sylvestris*.
Arbutus unedo; *Hedera helix;* *Laurus nobilis;* *Nerium oleander;* *Viburnum tinus*	Lorenzini et al., 1999	1 year-old plants in fumigation chamber	Ozone, single treatment at 200 ppb per 5 hours.	Visible symptoms on *A. unedo* and *N. oleander*. Reduction of photosynthetic activity in all species.
Arbutus unedo; *Myrtus communis;* *Pistacia lentiscus;* *Pistacia terebintus*	Skelly et al., 1999	Seedlings in OTC	Charcoal filtered air (50% ambient); non filtered air (96% ambient); open air, during a growth season	Visible symptoms on all the species investigated, in filtered and in air
Olea europaea	Minnocci et al., 1999	5 year-old olive plants (*Olea europaea* L. cvs. Frantoio and Moraiolo) in fumigation chamber	Ozone (<3 and 100 ppb) per 120 days, 5 h d^{1}	Frantoio: reductions in photosynthetic activity (57%) and stomatal conductance (69%); decrease of stomatal opening, increase of stomatal density Moraiolo: necrotic spots; decrease of stomatal conductance; decrease of stomatal opening, increase of stomatal density
Pinus halepensis	Soda et al., 2000	3 year-old potted seedlings in open air	AOT40 20 ppm.h during a growth season with hourly peaks over 100 ppb.	Visible symptoms; ultrastructural alterations in the mesophyll
Arbutus unedo	Bussotti et al., 2002	2 years-old seedlings in fumigation chambers	Ozone exposure at 0, 50 and 100 ppb for 21 days, 5 h d^{-1}	Visible symptoms at 50 and 100 ppb; structural changes in the epidermis and walls more pronounced at 100 ppb.

the new leaves sprout. So, high spring ozone levels may be more dangerous than the summer ones. Furthermore, because of the emission of isoprene and monoterpenes, background summer levels of ozone are naturally higher in Mediterranean ecosystems than in other environments, so that plants are perhaps normally adapted to moderate levels of this pollutant. Yet, ozone-induced symptoms have been observed, although sporadically, in various Mediterranean forest species, suggesting that the influence of certain environmental factors can modify the situation and increase the plants' sensitivity to this pollutant. Visible symptoms and physiological disorders have been reproduced in Mediterranean species in experimental exposure conducted in controlled and semi-controlled environments. Worthy of note are the Mediterranean-mountain populations, that is the southern provenances of forest species very common throughout Europe. The behaviour towards ozone of some of these species (e.g. beech and silver fir) has been investigated on a European scale, however the findings of these studies cannot be extrapolated to southern populations because of the genetic, morphological and ecological differences. The data available appear to suggest that these provenances have a greater resistance to ozone.

The sensitivity of Mediterranean plant species to ozone varies considerably and is dependent on intra- and infra-specific differences as well as on ontogenetic factors, on the local availability of water and other factors such as soil fertility. The combination of these factors can modify plants' biological response. For example, in natural conditions of water shortage, even sensitive species such as *Pinus halepensis* do not appear to be particularly threatened (Barnes *et al*., 1999).

In order to ensure the practical applicability of environmental protection policies, it is extremely important to establish communication networks between environmental protection and economic interest protection sectors (Innes and Price, 1999; Winter, 1999). In the Mediterranean region economic interests are hardly ever related to timber production; it would be more realistic in this region to envision a cooperation with sectors involved in land conservation and tourism. For example, an important aspect of the photochemical smog-induced damage is the air's loss of transparency (Copeland, 1999), which clearly jeopardizes enjoyment of the landscape. Furthermore, one should not neglect the impact of ozone on human health. One should make it clearer that protecting the health of ecosystems and protecting the health of mankind are two aspects of the same problem, and can be addressed by the same policies.

To conclude, we feel that it would be useful to list briefly the gaps in our current scientific knowledge, which make difficult the establishment of a serious environmental protection policy against ozone in Mediterranean ecosystems:

- in the Mediterranean region, ozone climatology is still to a large extent unknown; equally, little is known of ozone exposure except in summer, or of the role of biogenic emissions in determining the background levels of this pollutant;
- direct effects of ozone on Mediterranean plant species are still to a large extent unknown, since there is a lack of specific and realistic cause-effect experiments;
- the sensitivity of southern provenances (Mediterranean-montane) of species common throughout Europe (e.g. beech, silver fir) still needs to be investigated;
- the impact of ozone on typically Mediterranean plant communities, such as coppices, is totally unknown;
- it is necessary to identify the most sensitive sectors within each ecosystem (tree renewal, meadows, herbaceous species etc.), i.e. those that can be used as "response indicators".

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